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Spectator Processes and Baryogenesis

W. Buchmüller
Deutsches Elektronen-Synchrotron DESY, 22603 Hamburg, Germany

M. Plümacher
Theoretical Physics, University of Oxford, 1 Keble Road, Oxford, OX1 3NP, United Kingdom

Abstract

Spectator processes which are in thermal equilibrium during the period of baryogenesis influence the final baryon asymmetry. We study this effect quantitatively for thermal leptogenesis where we find a suppression by a factor O(1).

The cosmological baryon asymmetry is naturally explained by thermal leptogenesis, i.e. the out-of-equilibrium decays of heavy Majorana neutrinos [1]. This mechanism has been studied in detail by several groups [2], and it has been shown that the observed baryon asymmetry can be obtained over a wide range of parameters which are consistent with the observed properties of light neutrinos.

In a complete analysis decays, inverse decays and various scattering processes in the primordial plasma have to be taken into account in order to get a reliable estimate of the generated baryon asymmetry [3, 4]. In all previous analyses only the chemical potential μ_L of the standard model (SM) leptons was treated as a dynamical variable during the process of leptogenesis. All other chemical potentials, and also the baryon asymmetry, were then obtained from μ_L assuming thermal equilibrium after the period of leptogenesis.

However, this picture is incorrect. The duration τ_L of leptogenesis, which is driven by the out-of-equilibrium decays of heavy Majorana neutrinos, is larger than the Hubble time, $\tau_L > 1/H$. On the other hand, many processes in the plasma, in particular the sphaleron processes, are in thermal equilibrium, i.e. $\tau_i = 1/\Gamma_i < 1/H$. Hence, many spectator processes in the plasma are faster than leptogenesis. As a consequence the chemical potentials of particles in thermal equilibrium are changed already during the process of leptogenesis. In the following we study the effect of these spectator processes on the final baryon asymmetry in the framework of the SM with additional heavy Majorana neutrinos N_j.

Boltzmann equations

The most important processes that have to be considered are decays and inverse decays, whose reaction densities will be denoted by $\gamma_{D,j}$ in the following, top-quark neutrino scatterings mediated by a SM Higgs in the s- or t-channel, denoted by $\gamma^j_{\phi,s}$ and $\gamma^j_{\phi,t}$, and $\Delta L = 2$ processes mediated by heavy right-handed neutrinos in the s- or t-channel, denoted by γ_N and $\gamma_{N,t}$ (cf. [2]). Hence, in addition to the lepton number Y_L we also have to consider the chemical potentials of the Higgs doublet ϕ, of the quark doublets Q and of the right-handed top quarks t. Since the Yukawa couplings of up and charm quarks are significantly smaller they do not have to be considered here. We will use the following notation for the particle number asymmetries:

$$Y_\mathrm{H} = \frac{n_\phi - n_{\bar\phi}}{s}, \qquad Y_\mathrm{Q} = \frac{n_Q - n_{\bar Q}}{s} \quad \text{and} \quad Y_\mathrm{T} = \frac{n_t - n_{\bar t}}{s}\ , \tag{1}$$

where s denotes the entropy density of the universe and n_i are the number densities of the corresponding particles.

Taking these chemical potentials into consideration one obtains after a straightforward calculation the following set of Boltzmann equations for the evolution of the number of heavy Majorana neutrinos Y_{N_j} and the lepton asymmetry Y_{L}:

$$\frac{\mathrm{d}Y_{N_j}}{\mathrm{d}z} = -\frac{z}{sH(M_1)}\left(\frac{Y_{N_j}}{Y_{N_j}^{\mathrm{eq}}}-1\right)\left(\gamma_{D,j}+2\gamma^1_{\phi,s}+4\gamma^1_{\phi,t}\right) \tag{2}$$

$$\begin{aligned}\frac{\mathrm{d}Y_{\mathrm{L}}}{\mathrm{d}z} = -\frac{z}{sH(M_1)}\Bigg\{&\sum_j\left[\frac{1}{2}\left(\frac{Y_{\mathrm{L}}}{Y_l^{\mathrm{eq}}}+\frac{Y_{\mathrm{H}}}{Y_\phi^{\mathrm{eq}}}\right)-\varepsilon_j\left(\frac{Y_{N_j}}{Y_{N_j}^{\mathrm{eq}}}-1\right)\right]\gamma_{D,j}\\ &+2\left(\frac{Y_{\mathrm{L}}}{Y_l^{\mathrm{eq}}}+\frac{Y_{\mathrm{H}}}{Y_\phi^{\mathrm{eq}}}\right)(\gamma_N+\gamma_{N,t})\\ &+\sum_j\Bigg[\left(\frac{Y_{N_j}}{Y_{N_j}^{\mathrm{eq}}}\frac{Y_{\mathrm{L}}}{Y_l^{\mathrm{eq}}}+\frac{Y_{\mathrm{T}}}{Y_t^{\mathrm{eq}}}-\frac{Y_{\mathrm{Q}}}{Y_q^{\mathrm{eq}}}\right)\gamma^j_{\phi,s}\\ &+\left(2\frac{Y_{\mathrm{L}}}{Y_{\mathrm{L}}^{\mathrm{eq}}}+\left(\frac{Y_{\mathrm{T}}}{Y_t^{\mathrm{eq}}}-\frac{Y_{\mathrm{Q}}}{Y_q^{\mathrm{eq}}}\right)\left(\frac{Y_{N_j}}{Y_{N_j}^{\mathrm{eq}}}+1\right)\right)\gamma^j_{\phi,t}\Bigg]\Bigg\}\ .\end{aligned} \tag{3}$$

Here $Y_{N_j}^{\mathrm{eq}}$, Y_l^{eq}, Y_ϕ^{eq}, Y_q^{eq}, and Y_t^{eq} are the ratios of number density and entropy density for Majorana neutrinos, lepton doublets, Higgs doublet, quarks doublets and right-handed top-quarks, respectively. Further, we have assumed that all chemical potentials and CP asymmetries are small, and we have linearized the Boltzmann equations in CP and particle asymmetries. Setting all particle number asymmetries, except Y_{L}, to zero one recovers the Boltzmann equations that have been studied previously [3, 4].

It is interesting that the Boltzmann equation (2) for Majorana neutrinos is not modified to leading order in the chemical potentials. Similarly, the terms linear in ϵ_j, which are responsible for the generation of a lepton asymmetry in eq. (3), remain unchanged whereas the washout terms are enhanced. Indeed, decays of heavy Majorana neutrinos will create identical particle number asymmetries in lepton and Higgs doublets. Scattering processes in thermal equilibrium can change the ratio of Y_L and Y_H but not the sign. Further, since the top quark Yukawa coupling is in thermal equilibrium, the particle number asymmetries of quarks are given by the Higgs doublet asymmetry,

$$\frac{Y_{\mathrm{T}}}{Y_t^{\mathrm{eq}}}-\frac{Y_{\mathrm{Q}}}{Y_q^{\mathrm{eq}}}=\frac{Y_{\mathrm{H}}}{Y_\phi^{\mathrm{eq}}}\ . \tag{4}$$

Hence, since Y_L and Y_H have the same sign, every washout term in eq. (3) is enhanced.

Due to SM gauge, Yukawa and non-perturbative sphaleron interactions not all chemical potentials are independent. In the simplest case, when all SM interactions are assumed to be in thermal equilibrium, all chemical potentials can be expressed in terms of a single

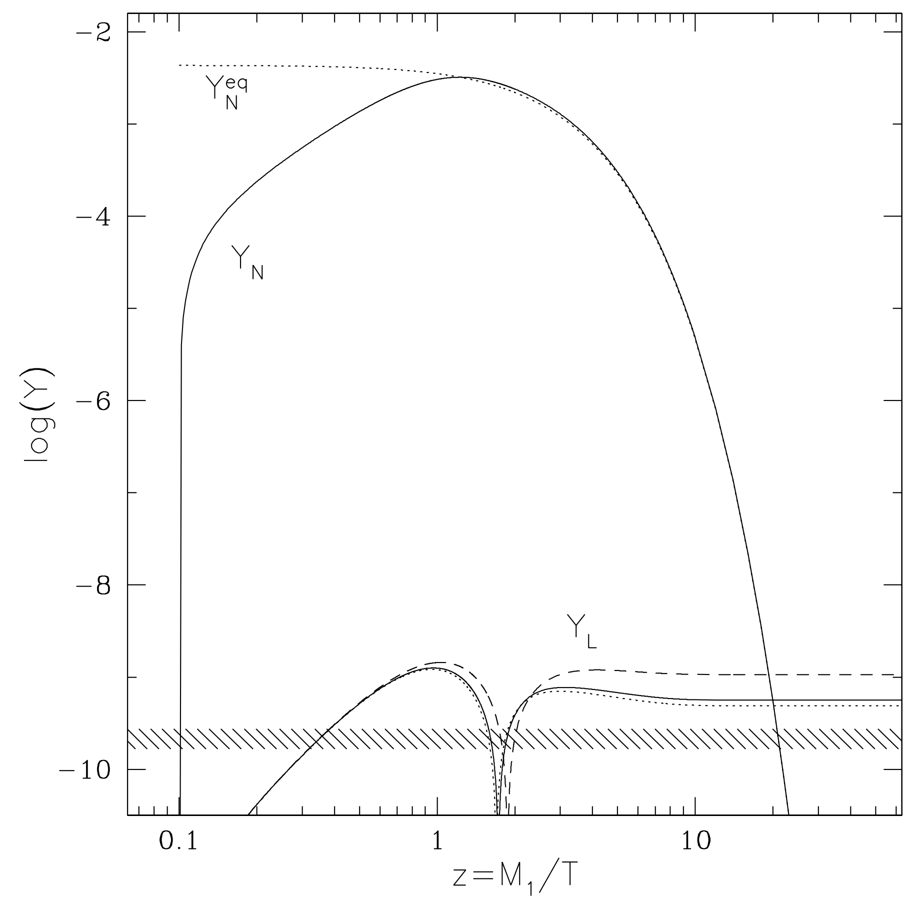

Figure 1: *Solutions of the Boltzmann equations. Neglecting the chemical potentials of quarks and Higgs fields gives the dashed line for the lepton asymmetry Y_{L}, whereas the solid and dotted lines correspond to setting $N_F = 1$ or $N_F = 3$ in the Boltzmann eq. (5).*

chemical potential, which can be chosen to be μ_l (cf. [2]). In this case the Boltzmann equation (3) for the lepton number takes the following form

$$
\begin{aligned}
\frac{\mathrm{d}Y_{\mathrm{L}}}{\mathrm{d}z} \;=\; & -\frac{z}{sH(M_1)}\left\{\sum_j\left[\frac{1}{2}\frac{14N_F+3}{6N_F+3}\frac{Y_{\mathrm{L}}}{Y_l^{\mathrm{eq}}} - \varepsilon_j\left(\frac{Y_{N_j}}{Y_{N_j}^{\mathrm{eq}}}-1\right)\right]\gamma_{D,j}\right. \qquad (5) \\
& + 2\frac{14N_F+3}{6N_F+3}\frac{Y_{\mathrm{L}}}{Y_l^{\mathrm{eq}}}\left(\gamma_N+\gamma_{N,t}\right) \\
& \left. + \frac{Y_{\mathrm{L}}}{Y_l^{\mathrm{eq}}}\sum_j\left[\left(\frac{Y_{N_j}}{Y_{N_j}^{\mathrm{eq}}}+\frac{4N_F}{6N_F+3}\right)\gamma^j_{\phi,s} + \left(2\,\frac{8N_F+3}{6N_F+3}+\frac{4N_F}{6N_F+3}\frac{Y_{N_j}}{Y_{N_j}^{\mathrm{eq}}}\right)\gamma^j_{\phi,t}\right]\right\}\,.
\end{aligned}
$$

Hence, taking the chemical potentials of all particles in the plasma into account enhances the washout processes by a factor $\mathcal{O}(1)$.

Numerical results

The structure of couplings between right-handed Majorana neutrinos and SM fields is model dependent. However, generically the lightest right-handed neutrino, which is responsible for the final lepton asymmetry, is coupled predominantly to SM quarks and leptons of the third generation. Hence, as a first approximation, we can neglect the first two generations of SM quarks and leptons and numerically solve the Boltzmann eqs. (2) and (5) assuming one generation of light fermions with Yukawa interactions in thermal equilibrium, i.e. setting $N_F = 1$ in eq. (5).

The result is shown in fig. 1, where we have used a parametrization of neutrino masses and Yukawa couplings based on a $SU(5) \times U(1)_F$ family symmetry described in ref. [5]. We have superimposed the result obtained when all chemical potentials, except lepton number, are neglected, which formally corresponds to setting $N_F = 0$ in eq. (5). To illustrate the effect of additional fermions we have also included the results obtained when setting $N_F = 3$. The final lepton number generated in these three cases is

$$Y_{\rm L} = \begin{cases} 1.1 \cdot 10^{-9} & \text{for} \quad N_F = 0 \ , \\ 5.6 \cdot 10^{-10} & \text{for} \quad N_F = 1 \ , \\ 4.9 \cdot 10^{-10} & \text{for} \quad N_F = 3 \ . \end{cases} \tag{6}$$

Hence, spectator processes in the standard model plasma reduce the final lepton asymmetry by a factor of about 2. The final baryon asymmetry is given by $Y_{\rm B} = -(8N_F + 4)/(14N_F + 9)Y_{\rm L}$.

We conclude that spectator processes generically influence washout effects and thereby modify the generated baryon asymmetry by a factor $\mathcal{O}(1)$.

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